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A randomized controlled trial evaluating the use of an intelligent, fully automated 2D imaging system to detect lame cows and control lameness

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ABSTRACT

A fully automated 2-dimensional imaging system that uses machine learning to produce real-time mobility scores has been developed and previously externally validated using human mobility scores and foot lesion records as ground truth. This randomized controlled trial evaluated the effect of integrating this system into an early detection and prompt treatment lameness management protocol on a large dairy farm in the UK A total of 419 multiparous cows ≤30 d-in-milk (**DIM**) were randomly allocated to either a control (**CON**) group (n = 208), managed under the farm's standard protocol or an intervention (**AUTO**) group (n = 211). The CON protocol consisted of routine trims at early (approximately 80 DIM) and mid-lactation (approximately 180 DIM), and examination of cows identified as lame by farm staff. In addition to the CON protocol, weekly automated scores were obtained for AUTO cows. Any AUTO cow exceeding the pre-defined threshold (≥50, on a scale of 0 to 100) or those with a ≥20 points increase in absolute scores during the last 2 weeks were scheduled for examination and treatment. Lameness scores from monthly human mobility scoring sessions were compared between groups using Fisher's exact tests or Chi-squared tests, with relative risks (**RR**) and odds ratios (**OR**) calculated. Trimming events, foot lesion prevalence and severity, and number of hoof block applications required were compared between groups using Poisson regressions and Chi-squared tests. The effect on weekly average milk yield was assessed with linear mixed effects models. Culling hazard was assessed using Cox proportional hazards regression (**COXPHR**). Time to 1st artificial insemination (AI) and time to conception by 150 DIM were assessed with COXPHR, whereas odds for pregnancy to the 1st AI were assessed with binary logistic regression. Cows in the AUTO group had a lower proportion of cows that developed severe lameness (2.0% vs. 7.9%, RR = 0.25; 95% CI: 0.09–0.66; OR = 0.24; 95% CI: 0.08–0.69) and chronic lameness (3.9% vs. 9.8%, RR = 0.40; 95% CI: 0.18–0.91; OR = 0.38; 95% CI: 0.16–0.88) compared with CON cows. Cows in the AUTO group underwent 2.67 trimming events per cow compared with 1.83 in the CON group during the study period (as estimated marginal means). At the 180 DIM routine trim, the AUTO group had a higher proportion of lesion-free cows (22.4% vs. 12.0%) and a lower proportion of cows with moderate lesions (16.0% vs. 25.3%). The small subset of second-parity cows in the AUTO group had higher odds of conception to 1st AI (OR = 7.6; 95% CI: 1.6–36.7) and a greater hazard of conception by 150 DIM (HR = 3.1; 95% CI: 1.3–7.3) compared with their CON counterparts. No differences were detected for weekly average milk yield or culling risk. Our findings indicate that automated mobility monitoring can improve lameness control programs by reducing severe and chronic lameness and improving mid-lactation foot health in cows.

Key words: automated monitoring, dairy cattle, machine learning, mobility

INTRODUCTION

Lameness caused by infectious and non-infectious hoof lesions is prevalent across the global dairy production system (Solano et al., 2016; Griffiths et al., 2018; Mason et al., 2023; Tillack et al., 2024) and has been shown to have detrimental impacts on the economic viability of a dairy enterprise (Huxley, 2013). Research has highlighted the value of early detection (Groenevelt et al., 2014) and prompt effective treatment (Thomas et al., 2015, 2016) in the control of claw horn disruption lesions (**CHDL**s) in particular; the literature in this field was recently reviewed and summarized by Pedersen and Wilson (2021). Once a CHDL has been identified, then a therapeutic hoof trim, orthopedic hoof block (where the contralateral claw is non-painful), and non-steroidal anti-inflammatory drug (**NSAID**) administration has

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The list of standard abbreviations for JDS is available at adsa.org/jds-abbreviations-26. Nonstandard abbreviations are available in the Notes.

been shown to improve cure rates (Thomas et al., 2015), reduce the pain sensitivity (Sadiq et al., 2022), reduce the risk of culling (Wilson et al., 2022), and improve reproductive outcomes (Mason and Laidlaw, 2025) of cows affected. Brunt et al. (2025) identified several barriers to the adoption of the *Early Detection and Prompt Effective Treatment* (**EDPET**) principle. Farmers within the focus groups of that study cited time, and lack of ability to detect subtle changes in gait as being barriers to identifying dairy cows who would benefit from a hoof inspection.

Efforts have been made to automate the mobility scoring process with an aim to reduce the barriers described above. Tools utilized include infrared thermography (Stokes et al., 2012; Anagnostopoulos et al., 2021; Werema et al., 2023), ground reaction force detection (Bicalho et al., 2007), and computer vision technologies (Anagnostopoulos et al., 2023; Swartz et al., 2024; Higaki et al., 2025; Jia et al., 2025; Siachos et al., 2025), alongside using biomarkers to predict lameness (He et al., 2022; Randall et al., 2023; Cardoso et al., 2025). The above means of detection show promise, however none of them have been examined in relation to the animal's response derived from treatments associated with these detection methods.

Recent publications have highlighted the ability of the CattleEye system (CattleEye Ltd., Belfast, UK) to automatically detect lameness in dairy cattle performing similarly to human mobility scorers (Anagnostopoulos et al., 2023; Swartz et al., 2024; Siachos et al., 2025). The CattleEye system is a commercially available video surveillance tool utilizing a 2D camera and machine learning algorithm to ascribe a mobility index to individual cows. This system has been shown to be able to reliably identify cows as they pass under the camera (Swartz et al., 2025) and presents the opportunity to reduce the barriers present in implementing the EDPET principle. Furthermore, the system is designed to detect more subtle changes to gait daily, potentially allowing for more regular screening of cattle for lameness than human mobility scorers may permit. This system has so far been compared with human mobility scorers (Anagnostopoulos et al., 2023; Siachos et al., 2025), and also examined in its ability to detect hoof lesions (Swartz et al., 2024; Siachos et al., 2025). However, how animals respond to treatments derived from this system in comparison to conventional lameness management systems is still unknown. Our study aimed to evaluate the efficacy of the 2D intelligent camera system in the implementation of the EDPET protocol through a randomized controlled trial utilizing cow mobility and reproductive outcomes under real farm conditions.

MATERIALS AND METHODS

Ethics statement

The study was approved by the University of Liverpool Veterinary Research Ethics Committee (Reference VREC1320) and was designed, conducted and reported in line with the REFLECT guidelines for reporting randomized controlled trials (O'Connor et al., 2010).

Farm characteristics

This randomized controlled trial was conducted on a single commercial dairy farm in England, U.K selected for convenience and for their willingness to participate in the trial. The farm housed more than 2,000 Holstein cows (exact herd size is not reported to maintain farm anonymity) year-round, which were milked 3 times daily in a rotary parlor. Sample size calculations were conducted using G*Power version 3.1.9.7 (Erdfelder et al., 2009), based on the expected reduction in lameness prevalence, from a baseline of 30% in the control group, reflecting the average lameness prevalence recorded in cows from these 3 pens in previous scoring sessions, to 18% in the intervention group, a relative reduction of approximately 40%. Assuming a 2-sided α of 0.05 and 80% power, a total of approximately 400 cows (200 per group) were required.

Cows were housed on typical 3-row free-stall barns deep-bedded with recycled manure solids, at a stocking rate of one cow per stall. The milking parlor surface and approximately a third of the passageway length from the barns to the holding area were covered with rubber mats. A rubber mat in a strip of single-cow width, also partially covered the 4 m-wide slatted return passageway from the milking parlor to the barns, for approximately one-third of its total length. All alleyways inside the barns housing the cows, the holding area and the loafing areas had a grooved solid concrete surface.

All milking cows were foot bathed twice daily with 4% formalin and once a week with 10% copper sulfate through stainless-steel footbaths measuring 3.7 m long and 0.6 m wide that were automatically emptied and refilled after every 200 cow passages (Hoofcount Ltd., Lancashire, UK). The farm was equipped with 2 identical footbaths placed side by side to ensure quick cow flow.

Enrolment

Multiparous cows were enrolled in the trial on a rolling weekly basis from July 27 to December 7, 2023. Eligible cows were those moved from the fresh cow pen into one of the 3 main lactation pens (designated as pens A, B, and C), where they remained housed for the whole duration of the study. These pens housed exclusively multiparous cows. At the time of enrolment, cows had a median of 13 DIM (range: 6 to 30 DIM). Enrolled cows were commingled with non-study cows within each pen, totaling approximately 780 cows across the 3 pens. We did not enroll any primiparous cows as these were moved into different pens throughout their lactation on this farm and their monitoring would be practically unfeasible. Weekly, the first author identified the cows that were moved from the fresh cow pen into pens A, B and C through the farm's management software, and randomly allocated them into the control (**CON**) or the intervention (**AUTO**) group within each pen, using the RAND formula in an Excel spreadsheet. We included only cows that were ≤30 DIM and that had not been foot trimmed during the previous 30 d.

Human mobility scoring records

The first author, a qualified veterinarian and experienced RoMS-accredited (Register of Mobility Scorers Limited, Wimborne, UK) mobility scorer, performed whole-milking-herd mobility scoring sessions monthly, using the 0–3 4-grade AHDB scoring system, with scores 2 and 3 considered as lame (Whay et al., 2003). Using a voice recorder, the cow ID (freeze brand number located on the rear thigh near the tail or ear-tag number if the freeze brand was unclear) and the mobility score of cows exiting the milking parlor and walking on level grooved concrete, were recorded. All records were later transcribed into Excel spreadsheets. A total of 9 monthly mobility scoring sessions were conducted. However, since cows were enrolled on a rolling basis, these sessions were subsequently matched to each cow's lactation stage using their calving date and were assigned to one of the 1st through 5th monthly mobility scoring sessions based on their DIM. On each of these sessions, the 4-grade (0/1/2/3) and binary-converted (0,1/2,3) human mobility scores are referred to hereafter as **HMS** and **HMS_BIN**, respectively. Severe lameness was defined as a mobility score of 3, while chronic lameness was defined as repeated lameness (scores of 2 or 3) over 2 or more (**CHRONIC_2S**) and over 3 or more (**CHRONIC_3S**) consecutive mobility scoring sessions. For ethical reasons, following each scoring session the assessor informed the farmer of any score 3 cow, regardless of study enrolment or allocation, and these were subsequently scheduled by the farmer for foot trimming at the next session, typically within 48 h. In addition, as the farmer did not have any access to the CattleEye scores during the study for the whole herd, a detailed report including cow IDs and mobility scores was provided to the farmer, after the removal of the IDs of enrolled study cows.

Automated mobility scores

The farm was equipped with a 2-dimensional surveillance camera placed at a height of 4 m above ground that provided overhead footage of cows walking on a level, solid, grooved concrete surface in the exit passageway of the milking parlor. As described in previous studies (Anagnostopoulos et al., 2023; Siachos et al., 2025), the system produces a mobility score on a continuous 0–100 scale (from perfect mobility to severe lameness), with each 25-point increment corresponding to one grade of the 0–3 4-grade AHDB scoring system, where cows with scores 2 and 3 are considered lame (Whay et al., 2003). Details about the system's setup, functional characteristics, and performance have also been provided extensively in previous publications (Anagnostopoulos et al., 2023; Swartz et al., 2024; Siachos et al., 2025).

The farmer and farm staff had no access to the data during the entire study period. Weekly, the same researcher downloaded the data from the app and calculated the weekly average automated mobility score (**WAVG**) for each enrolled cow.

Intervention

Cows in both groups were managed under the current farm's protocol, which consisted of routine trims at approximately 80 DIM and 180 DIM, and at pre-drying-off, examination and treatment of any cow identified as lame by farm staff. Farm staff would identify lame cows while walking through the milking parlor or while moving cows to and from their pens. No formal mobility scoring sessions were performed by farm staff. There was no additional intervention for cows in the CON group. Additional to the CON protocol, cows in the AUTO group, would be screened using the WAVG to identify and treat lame cows. Weekly, and on the same day of the week, cows in the AUTO group with a numeric score from the WAVG system ≥50 or an absolute increase of ≥20 points in their daily scores over the previous 2 weeks (identified by the system as "trending up"), were selected for treatment. The threshold for WAVG ≥50 was selected because it was used to validate the system's performance in previous studies (Anagnostopoulos et al., 2023; Siachos et al., 2025). The threshold used to identify trending up cows is an embedded feature of the system's application. To be eligible to be presented to the foot trimmer, animals could not have been trimmed during the last 28 d. Then, animals identified for treatment were entered remotely to the trimming list through the farm's herd management software and trimmed weekly. Farm staff and the foot trimmer were kept blinded to the enrolled cows and the allocation during the whole study period. A schematic overview of cow enrolment, allocation to study groups

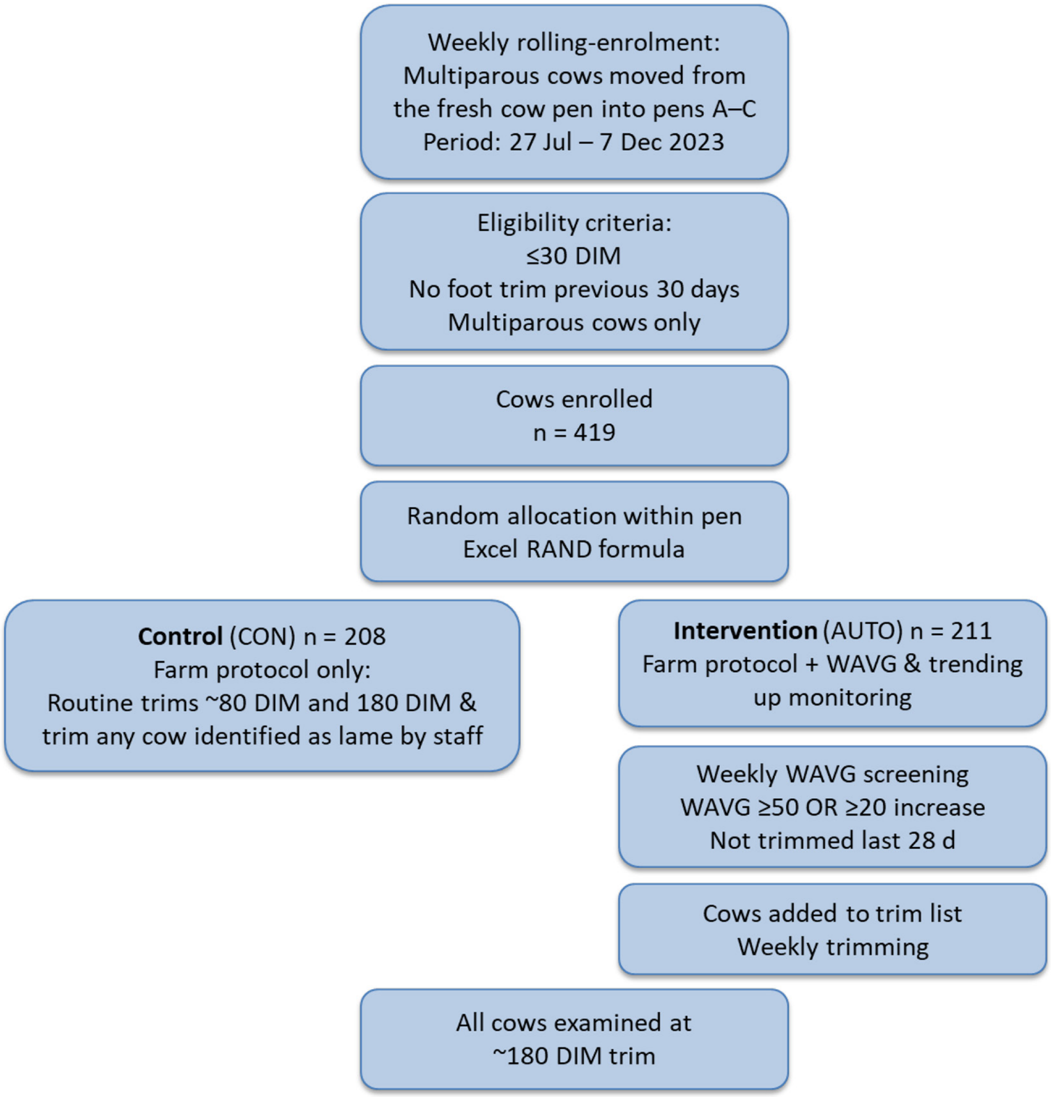

Figure 1. Flow diagram of cow enrolment, allocation, monitoring and intervention procedures. DIM = days-in-milk; CON = control group; AUTO = intervention group monitored by the automated system; WAVG = weekly average mobility score generated by the automated system.

and monitoring and intervention procedures is presented in Figure 1.

For the whole duration of the trial, study and non-study cows at pens A, B and C were trimmed by the same professional, Level 4 qualified foot trimmer twice weekly using a hydraulic chute. The trimmer performed a modified version of the Dutch 5-step method (Toussaint-Raven, 1989), which involves deeper and wider modeling of the hind lateral claw compared with the original method. Cows detected with CHDL received a therapeutic trim and application of a hoof block to the contralateral claw if possible but did not receive non-steroidal anti-inflammatory drugs (**NSAIDs**) routinely. Cows detected with active DD lesions were treated with a topical antibiotic spray and no NSAIDs. The authors did not intervene in treatment decisions during the study; these were applied consistently across AUTO and CON cows by the foot trimmer or by the farm veterinarian where required.

During each trimming session, the same trained veterinarian (first author) recorded the presence of any lesion on all 4 feet of the cows according to the International Committee for Animal Recording claw health atlas (Egger-Danner et al., 2014) and graded the severity of each lesion. The definition and grading methodology used are described in detail by Siachos et al. (2025).

Cows in both groups that were trimmed before 80 DIM did not undergo the early-lactation routine trimming session at 80 DIM. Additionally, all cows in both groups underwent the mid-lactation routine trimming session at 180 DIM, regardless of any previous trims, unless they had been trimmed within 3 weeks before 180 DIM. This time point was set as the completion of the study period. This allowed us to examine the feet of all cows enrolled in the study for any lesions at the same stage of lactation, enabling a consistent comparison. The same veterinarian recorded the presence and severity of any lesion in all 4 feet using the same definition methodology.

Cows were classified into 4 categories according to their foot lesion status as follows:

- Status 0 or "No lesions" included cows with no lesions.
- Status 1 or "Mild" included cows bearing at least one lesion of mild severity: double sole (**DS**), heel horn erosion (**HHE**), sole hemorrhage (**SH**) of grade 1, white line disease (**WL**) of grade 1, axial wall fissure (**AWF**) of grade 1 and digital dermatitis (**DD**) of grade 1.
- Status 2 or "Moderate" included cows bearing at least one lesion of moderate severity: sole ulcer (**SU**) of grade 1, SH of grade 3, WL of grade 2, AWF of grade 2, interdigital hyperplasia (**IH**) of grade 1 and 2, interdigital phlegmon (**IP**) of grade 1, and DD of grade 2.
- Status 3 or "Severe" included cows bearing at least one severe lesion: SU of grade >1, WL of grade 3, AWF of grade 3, toe ulcer (**TU**) of grade >0, IH of grade 3, IP of grade 2 and DD of grade 3.

Reproduction management

A voluntary waiting period of 50 d was implemented for multiparous cows on that farm. Estrus was detected using neck-mounted accelerometers (Heatime HR System, Allflex Livestock Intelligence, Ireland). No hormonal intervention was used for the first artificial insemination (**AI**). Initial pregnancy diagnosis was performed by the farm's veterinarian at 32–38 d post-AI by rectal ultrasonography. At the end of the study, the date at first AI and all subsequent AIs, the date at positive pregnancy diagnosis and the date that a "Do Not Breed" decision (**DNB**) was made, were retrieved through the farm's herd management software.

Milk production

The milking parlor was equipped with in-line milk meters (GEA Group AG, Düsseldorf, Germany) and the individual weekly average milk yield (**WAMY**) was retrieved for each cow through the farm's herd management software (DairyComp 305, Valley Ag Software, Tulare, USA).

Statistical analysis

Data were handled and analyzed with IBM SPSS v.29 (IBM Corp.; Armonk, NY) and MedCalc version 23.1.5 (MedCalc Software Ltd., Belgium).

Human mobility scoring

For the human mobility scoring records, data were analyzed across the 5 monthly mobility scoring sessions and cumulative outcomes for the entire study period. To evaluate differences in the prevalence of lameness and severe lameness at each scoring session, and proportion of cows with chronic lameness between the 2 groups, the Fisher's exact test (when expected frequencies in any cell were below 5 or zero) and the Chi-squared test were used, and the relative risk (**RR**), odds ratio (**OR**), and the number needed to treat (**NNT**) with 95% confidence intervals (**CI**s) were calculated.

Automated mobility scores

To evaluate the differences in the weekly average automated mobility score (**WAVG**) between the AUTO and CON groups over time, a linear mixed effects model (**LMM**) was applied. The dependent variable was the WAVG, while the independent variables included group (AUTO or CON), week (21 levels), and parity (3 levels: 2nd, 3rd, 4th or greater), as main effects. All 2-way and 3-way interactions were tested. The model accounted for the random effect of individual cows nested within pens for the repeated measurements.

To evaluate the time to the first occurrence of lameness, as recorded by the automated system, a survival analysis was performed using the Kaplan-Meier estimator and Cox proportional hazards regression. Kaplan-Meier survival curves were generated for the AUTO and CON groups, and survival distributions were compared using the log-rank test. The Cox regression model was used to identify the effects of group and parity on the hazard of the first occurrence of lameness. The model included group (CON or AUTO), parity (3 levels: 2nd, 3rd, ≥ 4th) and their interaction (parity × group) as covariates.

Weekly average milk yield

To evaluate differences in WAMY between CON and AUTO cows, a LMM was applied. The model's independent variables included group (CON or AUTO), week (21 levels), and parity (3 levels: 2nd, 3rd, ≥ 4th) as main effects, along with all 2-way interactions.

Reproduction performance

A Cox proportional hazards regression model was used to evaluate the potential effect of our intervention on the time to 1st AI by 150 DIM (**1stAI_150DIM**). The independent variables included group (CON or AUTO), parity (3 levels: 2nd, 3rd, ≥ 4th) and their interaction (parity × group).

A binary logistic regression model was applied to assess the potential effect of our intervention on the likelihood of successful 1st AI. The independent variables included group (CON or AUTO), parity (3 levels: 2nd, 3rd, ≥ 4th), their interaction (parity × group) and DIM at 1st AI. A Cox proportional hazards regression model was used to evaluate the potential effect of our intervention on the time to conception by 150 DIM (**CON_150DIM**). The independent variables included group (CON or AUTO), parity (3 levels: 2nd, 3rd, ≥ 4th), their interaction (parity × group) and DIM at 1st AI.

Kaplan-Meier survival curves were generated for the AUTO and CON groups, whenever a statistically significant effect of the group was identified ($P \leq 0.05$), and survival distributions were compared using the log-rank test.

For the time-to-event analyses, cows culled or designated as DNB before the end of the VWP were excluded as they were not eligible for breeding. All other cows that did not experience the event of interest, either 1st AI or conception, were right-censored at the time they left the risk set, or at the end of the observation period.

Culling hazard

To evaluate the effect of the group on the hazard of culling by 150 DIM and by 365 d after calving, 2 separate Cox proportional hazards regression models were applied. In both models, the independent variables included group (CON or AUTO), parity (3 levels: 2nd, 3rd, ≥ 4th), and their interaction (group × parity).

Count of foot trimming events and hoof block applications

Poisson regression models, using the Generalized Linear Models function of SPSS, were applied to evaluate the effect of the group on the count of foot trimming events (**TE**), hoof block applications (**HBA**) and hoof block applications per trimming event (**HBA_TE**) during the entire study period. Models included the group (CON or AUTO), parity (3 levels: 2nd, 3rd, ≥ 4th) and their interaction (parity × group) as independent variables. The log-link function was used adopting a Poisson distribution.

Count of foot lesion cases per trimming event during the entire study period

Poisson regression models were also used to evaluate the effect of the group on the count of cases detected with at least one severe foot lesion (Status 3) or with at least one moderate and severe foot lesion (Status 2 and 3) per trimming event between groups during the entire study period. Models included the group (CON or AUTO), parity (3 levels: 2nd, 3rd, ≥ 4th) and parity × group interaction as independent variables.

Foot lesion records at the 180DIM routine trim

To evaluate differences in the proportion of cows in different foot lesion severity groups between the CON and AUTO groups at the 180 DIM routine trim, 2 separate chi-squared tests were performed. The first assessed the proportion across the 4 lesion severity categories. The second test assessed the proportion of cows with no lesions or only mild lesions (Class 0: Status 0 and Status 1) and compared it to the proportion of cows with moderate or severe lesions (Class 1: Status 2 and Status 3). Additionally, to account for potential parity effects, a multinomial regression (for the 4 lesion severity categories) and a binary logistic regression model (for the 2 classes) were also fitted, including the group (CON or AUTO), parity (3 levels: 2nd, 3rd, ≥ 4th) and their interaction (parity × group) as independent variables.

Model-building strategies

Across all multivariable models, an initial screening of potential explanatory variables was performed using univariable analysis, and variables with a $P < 0.20$ were included in the multivariable analysis. Group assignment was included in all multivariable models a priori.

For LMMs, the appropriate covariance structure was applied to model repeated measures within each cow, which produced the lowest Akaike's information criterion value (Cavanaugh and Neath, 2019). Final models were built following a backward stepwise (likelihood ratio) elimination method to remove explanatory variables with a non-significant association at $P > 0.10$. Interaction terms were also retained in the model if $P < 0.10$. The normality of the data was assessed through visual inspection of the normal Q-Q plot, while the homoscedasticity was evaluated through the plot of residuals vs. fitted values. The week of study was included as a categorical factor to allow for nonlinear temporal patterns in the repeated measurements collected over the study period. Estimated marginal means (**EMMs**) were computed for each group × week combination, and pairwise comparisons were performed using Bonferroni's confidence interval adjustment.

Cox proportional hazards regression models used a backward stepwise (likelihood ratio) elimination method to remove non-significant variables at $P > 0.10$. The assumption of proportional hazards was assessed by visually examining the log-log survival plots. Results are reported as hazard ratios (**HR**s) with 95% CI.

Binary and multinomial logistic regression models were built following a backward stepwise (likelihood ratio) elimination method to remove non-significant variables at $P > 0.10$, and the final model was selected based on the lowest −2 log-likelihood. The ORs with 95% CIs were computed to assess the strength of associations. Model fit was evaluated using the Hosmer-Lemeshow goodness-of-fit test (Hosmer and Lemeshow, 1980), and classification accuracy was assessed using the classification table with a decision threshold of 0.50.

RESULTS

A total of 419 cows were enrolled in this trial, with 208 assigned to the CON group and 211 to the AUTO group. Descriptive data by group on parity distribution and cumulative lameness management events, including the number of trimming events, hoof block applications, and recorded foot lesions of enrolled cows during the study period are presented in Table 1.

From the initial number of enrolled cows, the number of cows included in individual analyses varied due to culling, reproductive management decisions, missing data and incomplete records at specific time points. By 150 DIM, 60 study cows had been culled, with a further 42 cows culled by 365 d after calving. Regarding human mobility scores, 383 cows were scored at the first session (n of missing cows CON: 18, AUTO: 18), 366 at the second (n of missing cows CON: 26, AUTO: 27), 353 at the third (n of missing cows CON: 31, AUTO: 35), 331 at the fourth (n of missing cows CON: 41, AUTO: 46), and 310 at the fifth (n of missing cows CON: 55, AUTO: 52) monthly session. Reductions in the number of cows scored over time were likely due to culling, but also due to missing or unmatchable records, including cows not scored or incorrect IDs. Regarding reproductive management, 48 cows were labeled as DNB before the end of the study, with 19 of these labeled after the end of the VWP. Complete foot lesion records at the 180 DIM routine trimming session were available for 314 study cows. This reduction in numbers from the initially enrolled is likely due to both cow removals and farm-level logistics on the day of the scheduled routine trimming visit, whereby some eligible cows were not presented to the foot trimmer, which was not in our control.

Table 1. Average days-in-milk (DIM) at enrolment, distribution of enrolled cows by parity and by pen, and total number of trimming events, hoof block applications, and foot lesions during the study period by experimental group

Variable	Control	Intervention	Total
Average DIM at enrolment	13.9	14.7	14.3
Parity 2	18	16	34
Parity 3	92	95	187
Parity 4+	98	100	198
Cows at Pen A	73	74	147
Cows at Pen B	82	83	165
Cows at Pen C	53	54	107
Trimming events	350	545	895
Hoof block applications	45	55	100
Status 2 foot lesions[1]	79	117	196
Status 3 foot lesions[2]	50	61	111

[1]Status 2 foot lesions: cows with at least one moderate lesion.

[2]Status 3 foot lesions: cows with at least one severe lesion.

Human mobility scores

The prevalence of lameness (scores 2 and 3) and severe lameness (score 3) per monthly mobility scoring session and treatment group is shown in Table 2. No differences in lameness prevalence (scores 2 and 3) were detected in any monthly scoring session ($P \geq 0.141$). Neither was there any difference in the overall proportion of lame cows observed between the 2 groups over the study period ($P = 0.620$).

Regarding monthly severe lameness prevalence (score 3), no differences were detected in the 1st, 3rd, 4th, and 5th sessions between the AUTO and CON groups. However, in the 2nd monthly session, 4.9% (9/183) of CON cows were found to be severely lame versus 0.0% (0/183) of AUTO cows ($P = 0.002$). The RR was 0.05 (95% CI: 0.00–0.90, $P = 0.040$), and the OR was 0.05 (95% CI: 0.00–0.87, $P = 0.040$), indicating a 95% lower likelihood of severe lameness in AUTO cows during their 2nd monthly scoring session. The NNT was 20.4 (95% CI: 12.2–62.2), indicating that approximately 20 cows would need to be monitored by the automated system over the study period to prevent one additional case of severe lameness during the 2nd monthly scoring session compared with standard practice.

Moreover, the AUTO group had a lower overall proportion of cows with severe lameness (2%, 4/201) compared with CON cows (7.9%, 16/203) ($P = 0.006$), with RR of 0.25 (95% CI: 0.09–0.74, $P = 0.010$), and OR of 0.24 (95% CI: 0.08–0.72, $P = 0.010$), indicating that cows in the AUTO group had a 75% lower likelihood of developing severe lameness. The NNT was 17.0 (95% CI: 9.9–58.8), indicating that 17 cows would need to be monitored by the automated system over the study period to prevent one additional case of severe lameness compared with standard practice.

Table 2. Prevalence of lameness and severe lameness per monthly mobility scoring session and experimental group during the study period

	Lameness prevalence[1]		Severe lameness prevalence[2]	
Scoring session[3]	Control (%)	Intervention (%)	Control (%)	Intervention (%)
1	16.8	11.5	1.6	0.0
2	15.3	13.7	4.9*	0.0*
3	18.1	13.5	0.5	0.6
4	17.9	22.0	1.8	0.6
5	14.5	20.8	2.0	1.3

[1]Lameness prevalence: cows with mobility score 2 or 3 on the four-grade AHDB mobility scoring system per monthly scoring session.

[2]Severe lameness prevalence: cows with mobility score 3 on the four-grade AHDB mobility scoring system per monthly scoring session.

[3]Scoring sessions 1 through 5 correspond to monthly human mobility assessments from enrollment to completion of the study.

* Values differ significantly between groups (P = 0.002) in scoring session 2 for severe lameness prevalence.

For chronic lameness, there were no differences between the 2 groups in CHRONIC_2S (P = 0.56). However, CHRONIC_3S was detected in 9.8% (18/183) of CON cows compared with 3.9% (7/178) of AUTO cows (P = 0.030). The RR was 0.40 (95% CI: 0.17–0.94, P = 0.040), and the OR was 0.38 (95% CI: 0.15–0.93, P = 0.030), indicating a 60% lower likelihood of chronic lameness in the AUTO group. The NNT was 17.1 (95% CI: 9.1–151.5), indicating that approximately 17 cows would need to be monitored by the automated system over the study period to prevent one additional case of chronic lameness compared with standard practice.

Weekly Average Automated Mobility Scores

Although the pattern of automated mobility scores over time differed between groups (group × week interaction P = 0.007), there was no main effect of group assignment on WAVG across the study period (P = 0.26). Parity (P < 0.001) and week (P = 0.017) also had effects on WAVG. The variation of WAVG for the 2 groups during the study period is shown in Figure 2, as EMMs (±95% CI). Pairwise comparisons of the EMMs revealed differences in WAVG between the AUTO and CON groups during certain weeks, with AUTO cows having lower EMMs for WAVG in wk 3 (P = 0.090), wk 5 (P = 0.095), wk 8 (P = 0.004), wk 9 (P = 0.091) and wk 10 (P = 0.070).

The Cox regression showed that group and parity were significant predictors of the time to the first occurrence of lameness as detected by the system. Cows in the AUTO group had a lower hazard of being identified as lame compared with the CON group, with an HR of 0.90 (95% CI: 0.85–0.95, P < 0.001). The covariate-adjusted survival curves for the 2 groups are shown in Figure 3. The median survival time to the first occurrence of lameness, as identified by the system, was 83 d (95% CI: 78.4–87.6) for CON cows and 98 d (95% CI: 93.7–102.3) for AUTO cows (P = 0.002). Cows in 3rd and ≥ 4th parity had an increased hazard compared with 2nd parity ones, with an HR of 1.32 (95% CI: 1.18–1.45, P < 0.001) and 1.85 (95% CI: 1.65–2.08, P < 0.001), respectively.

Weekly average milk yield

Weekly average milk yield differed by week (P < 0.001) and parity (P < 0.001). The variation of WAVG for the 2 groups during the study period is shown in Figure 3, as back-transformed EMMs (±95% CI). Weekly average milk yield did not differ between groups (P = 0.14) or by the interaction of group and week (P = 0.73). A marginal parity × group interaction (P = 0.054) was observed, with 2nd parity cows in the CON group having overall higher EMMs (shown here as back-transformed estimates) for WAMY (48.8 L, 95% CI: 46.6–51.1) compared with their counterparts in the AUTO group (44.8 L, 95% CI: 42.3–47.5).

Reproduction performance

The final Cox regression model indicated no main effects of group (P = 0.680) and parity (P = 0.549) on the hazard of receiving the 1st AI by 150 DIM. Similarly, there was no parity × group interaction (P = 0.080).

A main effect of group assignment (P = 0.01) and a parity × group interaction (P = 0.024) on the likelihood of successful 1st AI was observed. Cows in the AUTO group had overall higher odds of successful 1st AI compared with CON cows (OR = 7.57, 95% CI: 1.6–35.6). However, due to the parity × group interaction, this positive effect was evident only among 2nd parity cows, the reference category.

There was also a main effect of the group (P < 0.001) and a parity × group interaction (P < 0.001) on the hazard of CON_150DIM. Cows in the AUTO group had a higher

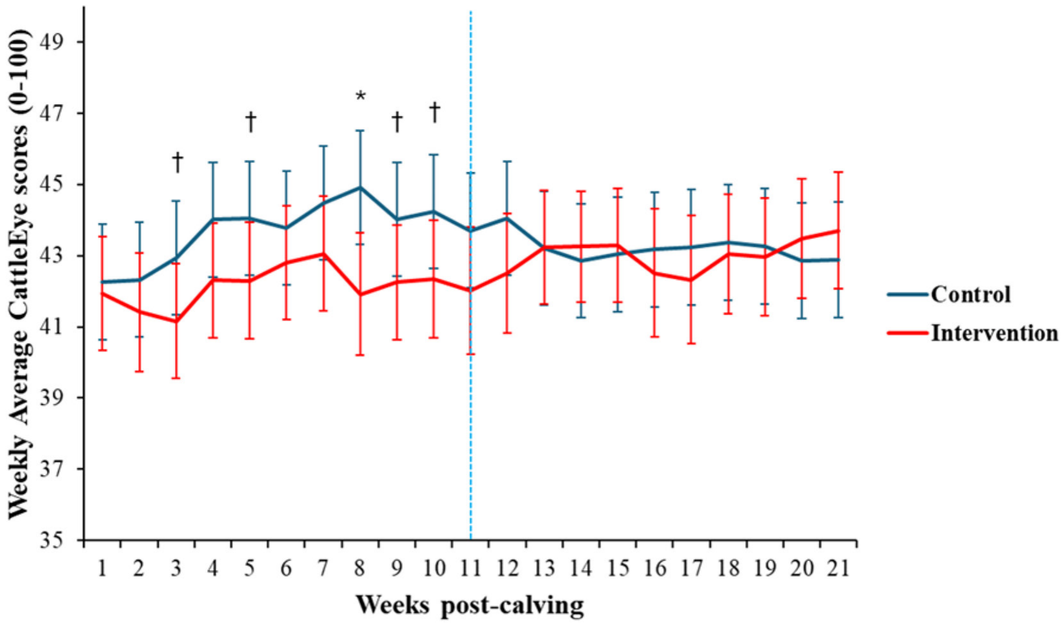

Figure 2. Estimated marginal means (±95% confidence intervals) derived from linear mixed models accounting for the effect of the experimental group and parity, showing the evolution of weekly average automated mobility scores during the first 21 weeks of lactation between cows in the control and the intervention group. A statistically significant association with the group × week interaction ($P = 0.007$) was observed. Pairwise comparisons indicated a statistically significant difference (*) in wk 8 ($P = 0.004$), while trends toward significance (†) were observed in wk 3, 5, 9 and 10 ($P \leq 0.095$). Dash line represents the timing of the routine trimming session at 80 d-in-milk (DIM). Cows that were trimmed before 80 DIM did not undergo that first session.

hazard compared with those in the CON group (HR = 3.10, 95% CI: 1.7–5.7). Days-in-milk at 1st AI were also associated with CON_150DIM (HR = 0.97, 95% CI: 0.96–0.98, $P < 0.001$), indicating that a longer calving to 1st AI interval was associated with a reduced hazard of CON_150DIM. Similarly, due to the parity × group interaction, this positive effect was evident only among 2nd parity cows, the reference category. The survival distributions between the 2 groups did not differ ($P = 0.778$), with the median survival time to CON_150DIM being 94 d for both groups, as identified by the Kaplan-Meier estimator. When breaking down the Kaplan-Meier survival analysis across parity levels, 2nd parity cows had a median survival time to CON_150DIM of 65 d (95% CI: 55–103) in the AUTO group and of 85 d (95% CI: 75–102) in the CON group. However, this difference was inconclusive, as the log-rank test was not statistically significant ($P = 0.147$).

Culling hazard

Neither the group nor the group × parity interaction had any effect on the hazard of culling by 150 DIM ($P = 0.690$, and $P = 0.800$, respectively) and on the hazard of culling by 365 d after calving ($P = 0.751$, and $P = 0.600$, respectively).

Count of foot trimming events and hoof block applications

An effect of group assignment was observed on the EMMs for the number of TE ($P < 0.001$). Cows in the CON group had an EMM of 1.83 (95% CI: 1.6–2.1) and cows in the AUTO group had an EMM of 2.67 (95% CI: 2.3–3.1) for TE, with an Incidence rate ratio (**IRR**) of 0.68 (95% CI: 0.59–0.78). On the other hand, the number of HBA did not differ between groups ($P = 0.246$). Cows in the CON group had an EMM of 0.28 (95% CI: 0.22–0.37) and cows in the AUTO group had an EMM of 0.35 (0.28–0.44) for HBA, with an IRR of 0.57 (95% CI: 0.57–1.16). Neither was any difference observed in HBA_TE between groups ($P = 0.842$). Cows in the CON group had an EMM of 0.072 (95% CI: 0.04–0.13) and cows in the AUTO group had an EMM of 0.078 (95% CI: 0.05–0.14) for HBA_TE, with an IRR of 0.92 (95% CI: 0.42–2.02).

Count of foot lesions during the entire study period

There were no differences in the EMMs for number of cases detected with at least one severe foot lesion (Status 3) or with at least one moderate and severe foot lesion (Status 2 and 3) per trimming event between groups ($P = 0.531$, and $P = 0.551$, respectively) during the entire study period. Regarding cases with at least one severe foot lesion (Status 3) per trimming event, CON cows had an EMM of 0.05 (95% CI: 0.02–0.13) and cows in the AUTO group had an EMM of 0.04 (95% CI: 0.02–0.10), with an IRR of 1.35 (95% CI: 0.53–3.42). Regarding cases with at least one moderate and severe foot lesion (Status 2 and 3) per trimming event, CON cows had an EMM of 0.09 (95% CI: 0.04–0.17) and cows in the AUTO group had an EMM of 0.11 (95% CI: 0.06–0.20), with an IRR of 0.80 (95% CI: 0.38–1.67).

Foot lesion records at the 180 DIM routine trim

When the proportions across the 4 lesion severity categories were assessed, a difference was observed between groups ($P = 0.039$). The AUTO group had a greater proportion of cows with no lesions (22.4%, 35/156) compared with the CON group (12.0%, 19/158; $P = 0.015$). In contrast, the CON group had a greater proportion of cows with moderate lesions (25.3%, 40/158) compared with the AUTO group (16.0%, 25/156; $P = 0.042$). Mild lesions were observed in 55.7% (88/158) of CON cows and 55.8% (87/156) of AUTO cows, and severe lesions were observed in 7.0% (11/158) of CON cows and 5.8% (9/156) of AUTO cows (Figure 5).

Cows with severe lesions in both groups had grade 3 DD (CON: 6/11, AUTO: 6/9) and grade 3 WL (CON: 5/11, AUTO: 3/9). In the CON group, the most frequent moderate lesions were grade 2 WL (24/40; 60%) and grade 3 SH (16/40; 40%), followed by grade 2 SU (4/40; 10%), grade 2 DD (4/40; 10%) and grade 2 IH (2/40; 5%). In the AUTO group, the most frequent moderate lesions were grade 2 WL (13/25; 52%) and grade 3 SH (12/25; 48%), followed by grade 2 DD (3/25; 12%). No cases of SU were detected in the AUTO group at the 180DIM routine trim.

Moreover, the multinomial logistic regression indicated a main effect of group assignment ($P = 0.029$) and parity ($P < 0.001$) on lesion severity classification. Compared with AUTO cows, cows in the CON group were more likely to have mild (Status 1) (OR = 2.06; 95% CI: 1.05–4.01, $P = 0.035$) and moderate lesions (Status 2) instead of no lesions (Status 0, reference category) (OR = 3.27; 95% CI: 1.46–7.33, $P = 0.004$).

When the proportions of the 2 classes of lesion severity were assessed (Class 0: no lesions or mild lesions; class 1: moderate or severe lesions), groups differed ($P = 0.037$). In the CON group, 67.7% (107/158) of cows fell into class 0, compared with 78.2% (122/156) in the AUTO group. Conversely, in the CON group, a greater proportion of cows (32.3%, 51/158) were classified into class 1 compared with the AUTO group (21.8%, 34/156; $P = 0.037$). Moreover, a main effect of group assignment ($P = 0.022$) and parity ($P = 0.005$) was detected on the binary lesion severity classification, with cows in the CON group being more likely to have moderate or severe

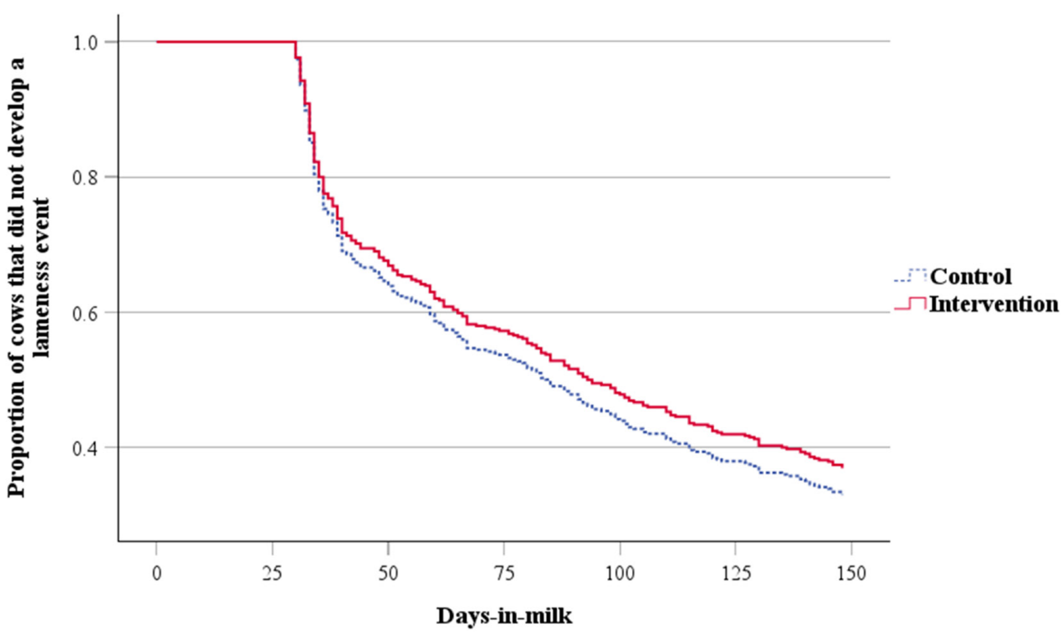

Figure 3. Covariate-adjusted Cox hazard curves showing the proportional hazard for having the first occurrence of lameness by 150 d-in-milk, as detected using the weekly average automated mobility scores. Cows in the group managed under the automated system (intervention) had a lower hazard of being identified as lame compared with cows in the control group, with a hazard ratio of 0.90 (95% confidence interval: 0.85–0.95, $P < 0.001$).

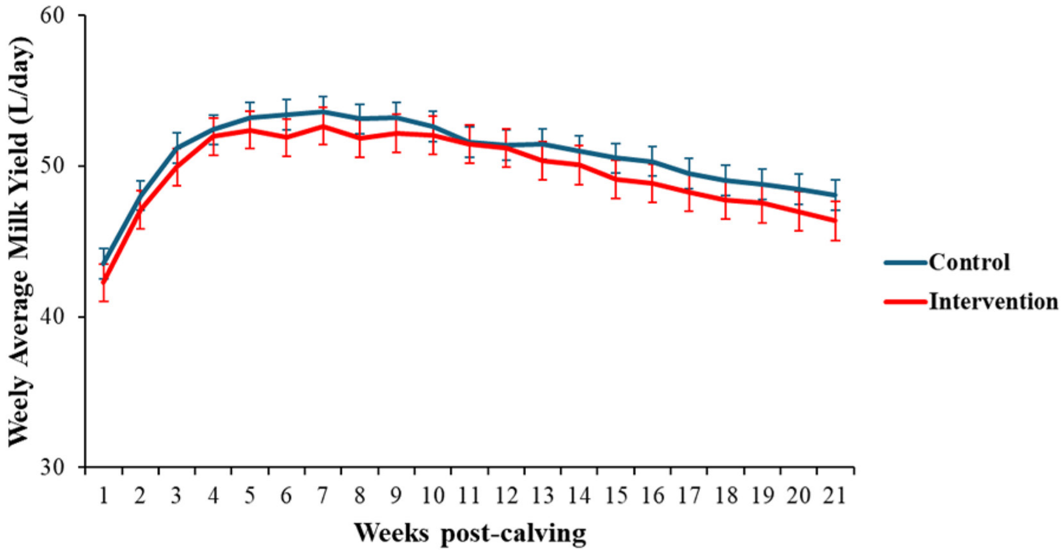

Figure 4. Estimated marginal means (±95% confidence intervals) for the weekly average milk yield over the first 21 weeks of lactation, derived from a linear mixed effects model accounting for the experimental group, week, and parity, between cows in the control and the intervention group. No statistically significant group effect or group × week interaction was detected.

lesions (Status 2 or 3) compared with AUTO cows (OR = 1.71; 95% CI: 1.02–2.87, $P = 0.041$).

DISCUSSION

In this randomized controlled trial, we evaluated the impact of integrating an intelligent, fully automated 2D imaging system into an early detection and prompt effective treatment protocol for lameness in dairy cows under commercial conditions. The primary aim was to assess whether real-time identification of lame cows based on machine learning algorithms, and prompt foot trimming could improve mobility outcomes, foot health and productivity. The intervention resulted in reduced proportion of cows with severe and chronic lameness, and improved foot health status at mid-lactation. The intervention was also associated with improved reproductive performance; however, this was only observed in the small population of 2nd parity cows and should therefore be interpreted with caution. These results suggest that automated mobility monitoring can improve the effectiveness of lameness management and mid-lactation foot health.

The intervention resulted in lower proportion of cows having chronic lameness (defined across 3 consecutive scoring sessions); there were approximately 2.5 times more chronic cases in the CON group. Chronic lameness represents a major welfare issue associated with persistent pain, altered gait patterns and long-term behavioral changes, such as reduced lying-standing transitions, decreased feed intake and impaired social interactions within the herd (Whay et al., 2003; Flower and Weary, 2006; Barker et al., 2009). Prolonged lameness at any degree is also viewed by stakeholders as "unacceptable." It directly compromises cow welfare, it has negative impacts on stockperson morale (Muir et al., 2025), and imposes considerable economic losses (Warnick et al., 2001; Green et al., 2002; Robcis et al., 2023). Chronic cases, of CHDLs, often persist across lactations (Pedersen and Wilson, 2021) and have lower cure rates (Thomas et al., 2016). This is partly due to permanent structural damage to the corium, the digital cushion and the pedal bone, along with alterations to horn growth patterns (Newsome et al., 2016; Randall et al., 2016; Wilson et al., 2021). Therefore, the observed reduction in chronic lameness is particularly important and suggests that automated monitoring facilitates earlier detection, preventing the progression of acute cases to chronic states.

Similarly, the intervention reduced the proportion of cows that developed severe lameness; there were approximately 4 times more cows identified with severe lameness in the CON group. Severe lameness necessitates prolonged recovery times and carries a higher risk of transitioning into chronic lameness if not addressed promptly (Whay et al., 2003; Thomas et al., 2015). Economic models show that severe lameness cases can cost more than twice as much comparing to mild or moderate cases due to higher treatment costs, greater milk loss, negative effects on fertility and increased culling rates (Charfeddine and Pérez-Cabal, 2017; Robcis et al., 2023). Close automated monitoring showed potential in preventing progression to severe cases, although measurable gains in productivity or reduced culling rates were not evident in this study.

The benefits of the intervention on lameness outcomes which were most apparent during the first 3 mo of lactation, were also shown from the evolution of the weekly automated mobility scores, which were consistently lower in the AUTO group during the first 12 weeks of lactation. Control cows remained sound for a shorter duration on average. The median time to first automated lameness event occurred 15 d earlier compared with AUTO cows. During early lactation, cows are at greater risk of developing CHDLs as they experience thinning of the digital cushion and of the sole soft tissues and increased mechanical loading on the claws (Newsome et al., 2016; Griffiths et al., 2024). After this period, the differences between groups diminished, probably because the early lactation routine trim at 80 DIM resolved some existing lesions in CON cows that had gone undetected by farm staff.

Our findings are consistent with previous work based on frequent human mobility scoring, where earlier detection followed by prompt therapeutic trimming reduced lesion severity and shortened the duration of lameness. These studies, using weekly or fortnightly scoring, reported better clinical outcomes when treatment followed soon after first identification, whereas delays to treatment were common under routine or standard farm practice and were associated with persistence of lameness and progression of lesions to severe states (Alawneh et al., 2012; Leach et al., 2012; Groenevelt et al., 2014). Managing cows with the automated monitoring system delivered the same principle of EDPET, while operating continuously and at scale.

As expected, the intervention resulted in more frequent trimming events per cow, by approximately 1.5 times compared with the CON group. Interestingly, no significant differences were detected in the total number of lesions or in their severity per trimming event, nor in the count of hoof block applications per trimming event throughout the study. However, cows in the AUTO group showed better foot health status at the mid-lactation routine trim, which was set as the completion time point of the study. Specifically, the AUTO group had a higher proportion of lesion-free cows and a lower prevalence of moderate lesions. This indicates that earlier intervention reduced the risk of progression from mild to more advanced lesion states. Moreover, the fact that SU were only detected in CON cows at the 180DIM hoof inspection, reinforces this point. The timely intervention during early lactation could have prevented mild CHDLs such as SH from progressing into more severe conditions with shared pathophysiology (SU).

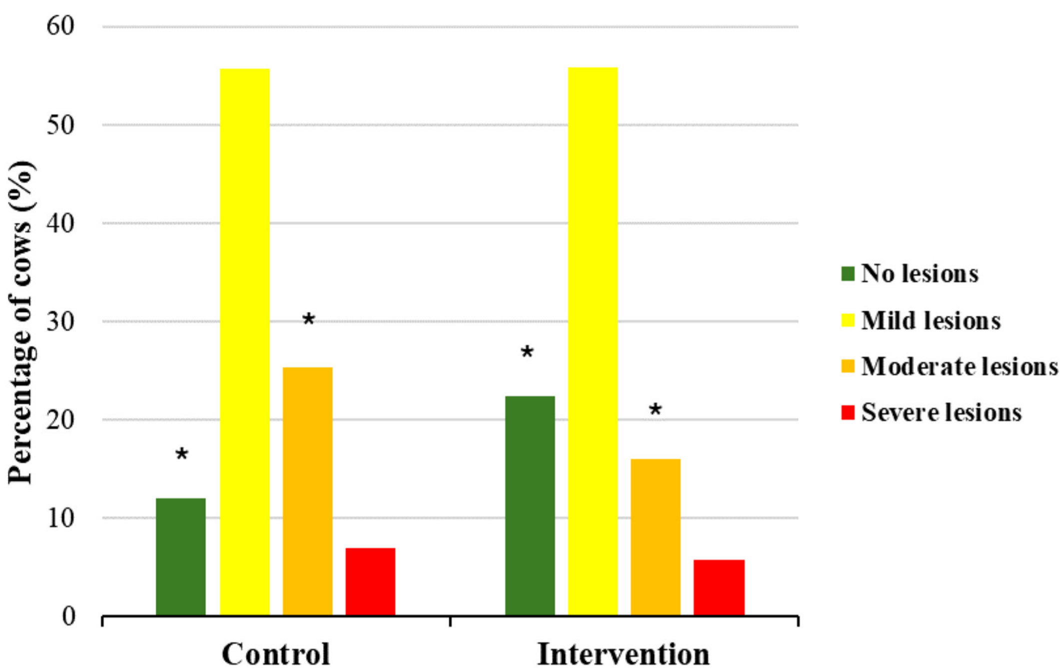

Figure 5. Proportions of cows at different foot lesion severity groups in Control (**CON**) and Intervention (**AUTO**) groups at the 180 d-in-milk routine trimming session. Cows were classified as having no lesions (green), mild (yellow), moderate (orange), or severe (red) lesions. A chi-squared test showed a statistically significant difference between groups ($P = 0.039$). More cows in the AUTO group had no lesions (22.4%, 35/156) than in the CON group (12.0%, 19/158; $P = 0.015$), while moderate lesions were more common in the CON group (25.3%, 40/158) than in the AUTO group (16.0%, 25/156; $P = 0.042$). Mild (CON: 55.7%, AUTO: 55.8%) and severe lesions (CON: 7.0%, AUTO: 5.8%) did not differ. Asterisks (*) indicate statistically significant differences between groups at $P < 0.05$.

The reproductive performance benefits observed were limited among the small population (n = 34) of 2nd parity cows in this study and results should therefore be interpreted with caution. These animals had higher conception rates to first AI and a higher likelihood of conception by 150 DIM following the intervention. Despite this effect not being observed to a wider extent and to older cows, it is well established that lameness impairs estrous expression and reduces conception rates (O'Connor et al., 2020; Mason and Laidlaw, 2025). By contrast, milk production did not differ between groups, with only a statistical tendency toward parity × group interaction, suggesting overall lower milk yield in 2nd parity cows in the AUTO group.

Understanding the impacts of age and lameness chronicity are vital to ensuring that lameness interventions are effective. A recent study conducted in heifers identified using NSAIDs as part of a lameness treatment reduced the risk of lameness and culling over a 3-year period (Wilson et al., 2022). However, the same study applied to cows in their second parity or higher yielded no significant results using the same outcomes (Wilson et al., 2025). The authors highlighted the role that chronicity may play in the recurrence of hoof lesions - in turn reducing the efficacy of their intervention. It is possible that we have observed some impacts of chronic hoof lesions in our population and understanding the impacts that this system may have on primiparous heifers warrants further investigation.

Further research is needed to evaluate the performance and impact of automated mobility monitoring across a wider range of farm environments with different herd demographics and variable lameness prevalence. Adjusting the pre-defined alert thresholds for lameness according to parity, using the historical automated mobility scores to increase detection accuracy, as shown in our previous work (Siachos et al., 2025), and lesion history from previous lactations may help optimize trimming decisions and minimize unnecessary interventions. Future work could also include a group of cows managed only with the automation detection system, without the farm's standard control protocol. Studies should also explore the effects of evaluating automated detection with standardized best-practice treatment protocols, including the use of NSAIDs for CHDLs. Moreover, following cows across multiple lactations is needed to quantify the long-term impacts on lesion recurrence and welfare implications. In addition, future studies should quantify the cost associated with more frequent trimming sessions and balance these against potential economic benefits arising from the reduction in severe and chronic lameness.

LIMITATIONS

Limitations of the present study should be acknowledged. First, the study was conducted on a single large commercial herd, which limits the generalizability of findings to farms with different layouts, herd demographics, lameness prevalence or management systems. However, the farm's housing system, lameness management and control protocols were typical of large dairy units in the UK and globally. Second, the same researcher who created the weekly trimming lists, also performed the human mobility scoring and foot lesion assessments, which could introduce unconscious observer bias. However, because the mobility scoring sessions involved the entire milking herd (over 2,000 cows), it was practically not possible for the observer to remember which cows were enrolled in the study or their group allocation by their freeze brand while the cows were moving through the scoring area. Nevertheless, farm staff and the foot trimmer were fully blinded to enrolment and group assignment, minimizing any risk of bias. First parity cows were not included, as these animals were managed in different pens that changed irregularly throughout lactation, making their continuous monitoring for the scope of this study impractical with the available resources. Although this limits the generalizability of our findings to multiparous cows, it was a necessary compromise to ensure the consistent follow-up of enrolled animals. Lastly, the treatment protocol for CHDLs applied on this farm did not involve routine NSAID administration, which may have influenced recovery rates and the impact of early identifying these lesions.

CONCLUSIONS

The integration of an intelligent, fully automated 2D imaging system into the routine lameness monitoring and management protocol in a large dairy farm was associated with significant reductions in severe and chronic lameness and improved mid-lactation foot health, and better reproductive performance, which must be interpreted cautiously as it was limited to the small number of second-parity cows. These benefits were attributed to the early detection of lameness and the targeted intervention for cows with lesions at an early stage of development. Future research should explore optimal implementation strategies, refine alert thresholds and investigate long-term outcomes across all parities.

NOTES

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